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# The Case of two Self-Enforcing International Agreements for Environmental Protection with Asymmetric Countries

**Dritan Osmani · Richard S. J. Tol**

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**Abstract** Non-cooperative game theoretical models of self-enforcing international environmental agreements (IEAs) that employ the cartel stability concept of D'Aspremont et al. (Can J Econ 16:17–25, 1983) frequently assume that countries are identical, and they can sign a single agreement only. We modify the assumption by considering two self-enforcing IEAs and also two types of asymmetric countries. Extending a model of Barrett (Oxford Econ Pap 46:878–894, 1994), we demonstrate that there are similarities between one and two self-enforcing IEAs. But in the case of few countries and high environmental damage we show that two self-enforcing IEA work far better than one self-enforcing IEA in terms of both welfare and environmental quality. Our

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simulation shows that only if all countries that have fewer benefits and higher cost from pollution abatement must build one coalition, there is hope that two myopic stable coalition can be formed. Moreover, if the cost-benefit functions of pollution abatement impose that the first myopic coalition is formed by countries, which have higher benefits and lower cost from pollution abatement, then two IEA's worsen abatement and welfare in comparison to one IEA. But, if the first myopic coalition is formed by countries, which have smaller benefits and higher cost from pollution abatement, then two IEA's improve abatement and welfare in comparison to one IEA.

**Keywords** Self-enforcing international environmental agreements · Non-cooperative game theory · Stability · Nonlinear optimization

## 1 Introduction

The formation and implementation of International Environmental Agreements (IEA) is the topic of a broad economic literature. A significant part of the literature uses game theory as a tool to understand the formation mechanism of IEAs. There are two main directions of literature on IEAs (for a review of current literature see (Finus 2003; Carraro and Siniscalco 1998; Ioannidis et al. 2000; Carraro et al. 2005). The first direction utilizes the concepts of cooperative game theory in order to model the formation of IEAs. This is a rather optimistic view, and it shows that an IEA signed by all countries is stable provided that utility is transferable and side payments are adequate (Chander and Tulkens 1995, 1997). The second direction uses the concepts of non-cooperative game theory to model the formation of IEAs. At the first level, the link between the economic activity and the physical environment is established in order to generate the economical-ecological model. This link is established through a social welfare function. The social welfare function captures the difference between the profit from pollution and the environmental damage. Following this approach, countries play a two stage-game. In the first stage, each country decides to join or not the IEA. In the second stage, every country decides on emissions. The main body of literature examining the formation of IEA within a two stage framework uses a certain set of assumptions. We mention below only the essential ones:

- Decisions are simultaneous in both stages.
- Countries are presented with single agreements.
- When defecting from coalition, a country assumes that all other countries remain in the coalition (this is a consequence of the employed stability concept of D'Aspremont et al. (1983) that allows only singleton movements and myopia).
- Within the coalition, players play cooperatively while the coalition and single countries compete in a non cooperative way.

Non-cooperative game theory draws a pessimistic picture of the prospect of successful cooperation between countries. It claims that a large coalition of signatories is hardly stable, and that the free-rider incentive is strong. The model explains the problems of international cooperation in the attendance of environmental spillovers,but cannot explain IEAs with high membership such as the Montreal Protocol. This calls for a modification of the standard assumptions. We mention in the following paragraphs some of the possible modifications.

Maybe the most important development is the work on coalition theory of Ray and Vohra (1994); Yi and Shin (1995); Yi (1997) and Bloch (1995, 1996); Bloch et al. (1997). They allow many coalitions to be formed, although they employ a different rule of forming coalitions. Ray and Vohra (1994) analyse Equilibrium Binding Agreements (a game in which coalitions can only break up into smaller coalitions), Bloch (1996) shows that the infinite-horizon Coalitional Unanimity game (game in which a coalition is formed if and only if all members agree to form it) yields a unique subgame perfect equilibrium coalition structure. Yi and Shin (1995) examine an Open Membership Coalitional game (in which nonmembers can join a coalition without the permission of existing members). Yi (1997) shows that in the Open Membership Coalitional game the grand coalition can be an equilibrium outcome for *positive externalities*. But for *positive externalities* in the Coalitional Unanimity game, the grand coalition will be rarely an equilibrium. He shows also that for the same game, the grand coalition can rarely be an equilibrium outcome for *negative externalities* due to free-rider problems.

*A sequential choice of emission levels* means there is a Stackelberg leader (a coalition of signatories), who takes into account the optimal choice of non-signatories that behave as Stackelberg followers (Barrett 1994, 1997a). Participants have an advantage towards non-participants as they chose the emissions level based on the reaction functions of non-participants.

Ecchia and Mariotti (1998) distinguish two problems in the standard model of self-enforcing IEA. In the basic model, countries are presumed to behave myopically by disregarding other countries' reaction when they make their choices. They modify this assumption by introducing the notion of *farsightedness*. If countries are farsighted, that is they can foresee other countries' reaction to their choices and incorporate them into their decisions, a new notion of stability has to be established. The authors demonstrate that if the idea of farsightedness is placed into the model, the likelihood of larger coalition increases. Considering asymmetric countries, *transfers* can help to increase membership and success of IEAs (Botteon and Carraro 1997; Carraro and Siniscalco 1993; Barrett 1997b).

Jeppesen and Andersen (1998) demonstrate that if some countries are committed to cooperation concerning their abatement implies that this group of countries presupposes a leader role in forming the coalition. The leading role allows them to evaluate potential aggregate benefits from increasing the coalition and device side payments to countries that have a follower role in order to attain optimum membership.

Hoel and Schneider (1997) integrate *a non-environmental cost function* from not signing the IEA which they call "non-material payoff". They find that, even in the absence of side payments the number of signatories is not very small.

Barrett (1997b) uses a partial equilibrium model to observe the effectiveness of trade sanctions in signing an IEA. He considers only traded goods that are linked to environmental problems. He explains that if the public good agreement is linked to a club agreement, such as a trade agreement, the membership in IEAs can be raised.

Botteon and Carraro (1997), Carraro and Siniscalco (1998), Breton and Soubeyran (1998) and Katsoulacos (1997) give similar conclusions.

Carraro et al. (2001) make obvious that the implementation of *a minimum participation clause* can help to improve the success of IEAs. Such a clause implies that a treaty only enters into force if a certain number of signatories has approved it. The minimum participation clauses are found in most IEAs in the past.

Endres (1996, 1997) shows that the bargaining outcome under the inefficient uniform emission reduction quota regime may have better-quality from an ecological and economic point of view than an efficient uniform tax rate in a two-country model. Endres and Finus (2002); Finus and Rundshagen (1998a,b) demonstrate that an inefficient emission reduction under the quota regime is rewarded by higher stability and higher membership.

This paper uses non-cooperative game theory in order to develop further a model from Barrett (1994). We are aware of the recent work on coalition theory by Ray and Vohra (1994); Yi and Shin (1995) and Bloch (1996); Bloch et al. (1997) who consider symmetric players. We think that modeling two self-enforcing IEA with asymmetric players (we present two types of players) can bring a better understanding of improving capacity of IEA's. We are less concerned with developing a general theory of coalition formation. Rather, we present and apply a method for computing the welfare and abatement improvement of two coalitions. The loss in generality is compensated by a gain in practically. The main contribution of this paper is the discussion on the *possibility of improving capability* (welfare, emission reduction and size) of two self-enforcing IEA with asymmetric players comparedto one self-enforcing IEA by modeling the IEA as a one-shot game. Another contribution is *a different formulation (as nonlinear optimization problem)* of finding $\alpha(\alpha N =$ the number of signatories) in extended Barrett's model. Although our work is less general than that of Yi and Shin, Bloch etc. we actually count up for asymmetric players and are able to compute the coalition sizes and optimal abatement levels. We would like to stress that we reinforce the conclusions of Asheim et al. (2006) and Carraro (2000) by following a different method, that is the nonlinear optimization.

In our modeling approach, the coalition of signatories (or the first coalition when we have two coalitions) behaves always like a Stackelberg leader. We consider as more realistic to assume that the countries react to climate change (as a consequence to coalition formation) in different stages (which is similar to Stackelberg game) and not simultaneously (which is similar to Nash-Cournot game). On the other side, it is considerable work to consider the Stackelberg game, and it follows that the Nash-Cournot case will be subject to further research.

In Sect. 2 we describe Barrett's model of one-self enforcing IEA and formulate it differently as a nonlinear optimization problem. In Sect. 3, we present our model for one-self enforcing IEA with asymmetric countries. In Sects. 4 and 5, we present our model for two-self enforcing IEA with symmetric and asymmetric countries. Section 6 discusses our simulation results, while section seven provide our conclusions. In the Appendix, different tables of results are presented.

## 2 Barrett's Model, One Self-Enforcing IEA with Symmetric Countries

For an IEA to be *self-enforcing* means that no single nonsignatory has an incentive to join an IEA (*External Stability*) and no single signatory has an incentive to withdraw from the agreements (*Internal Stability*). Furthermore, the coalition *has to be profitable*, that is the coalition members pay-off is greater than their pay-off in Nash's equilibrium. The IEA's have to be designed so that they are *self-enforcing* because of nonexistence of a supranational authority that can implement and enforce the agreements. The striking result of Barrett's research is that *a self-enforcing IEA* can be signed by a large number of countries only when the difference between fullcooperative and noncooperative payoffs is small. When this difference is large, *self-enforcing IEA* would be signed only by a small number of countries.

The model makes some important assumptions, which are:

- all countries are identical,
- each country's net benefit function is known and known to be known, etc. by all countries
- pollution abatement is the only policy instrument,
- abatement levels are instantly and costlessly observable,
- the pollutant does not accumulate in the environment,
- costs are independent of one another.

The abatement benefits function $B_i(Q)$, the abatement cost function $C_i(q_i)$ and the profit function $\pi$ of country $i$ are defined as:

$$B_i(Q) = b\left(aQ - Q^2/2\right)/N \tag{1}$$

$$C_i(q_i) = cq_i^2/2 \tag{2}$$

$$\pi_i = B_i(Q) - C_i(q_i) \tag{3}$$

$a \in R^+, b \in R^+$ and $c \in R^+$ parameters, $q_i$ amount of abatement of country $i$, $Q$ global abatement $Q = \sum_{i=1}^{N} q_i$, $N$ number of identical countries, each of them emits a pollutant.

The marginal abatement benefit and cost of country $i$ are linear, $b$ is the slope of marginal benefit and $c$ is the slope of marginal cost.

The full cooperative outcome is found by maximizing global net benefits $\Pi = \sum_{i=1}^{N} \pi_i$ with respect to $Q$. The *fullcooperative abatement levels* are:

$$Q_c = aN/(N+\gamma) \tag{4}$$

$$q_c = a/(N+\gamma) \tag{5}$$

$Q_c$ global abatement, $q_c$ individual's country abatement, $\gamma = c/b$.
*The noncooperative outcome* is found by maximizing country net benefits $\pi$ with respect to $q_i$. The *noncooperative abatement levels* are:

$$Q_0 = a/(1+\gamma) \tag{6}$$

$$q_0 = a/N(1+\gamma) \tag{7}$$

$Q_0$ global abatement, $q_0$ individual's country abatement.
It is obvious that $Q_c > Q_0$.

## 2.1 One Self-Enforcing IEA with Symmetric Countries

We have $\alpha N$ countries that sign the IEA (signatories) forming a coalition and $(1-\alpha)N$ countries that do not sign the agreements (nonsignatories). In the first stage, the coalition of signatories ($C_s$) try to maximize their net-benefits, the coalition behaves like Stackelberg leader (Barrett 1994). In the second stage, every nonsignatory try to maximize his own benefit (after observing the behavior of signatories), they behave like Stackelberg followers. Modelling $C_s$ as a cooperative game, *the Nash bargaining solution will require that each country undertake the same level of abatement*. This implies that if $Q_s$ is the total abatement of signatories and $q_s$ is the single signatory abatement then $Q_s = \alpha N q_s$. Let $Q_n$ be the total abatement of nonsignatories and $q_n$ be the single nonsignatory abatement. As countries are identical *the Nash equilibrium requires that $q_n$ are identical* thus $Q_n = (1-\alpha)Nq_n$. The reaction function of nonsignatories is given by:

$$Q_n(\alpha, Q_s) = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha) \tag{8}$$

In order to find $Q_s(\alpha)$ the following nonlinear optimization problem needs to be solved:

$$\max \Pi_s(Q_s) \quad s.t \quad (8) \tag{9}$$

where $\Pi_s$ is the total benefit of signatories, $\pi_s$ is the single benefit of a signatory, $\Pi_s = \sum \pi_s$. The solution is:

$$Q_s^*(\alpha) = a\alpha^2 N\gamma/[(\gamma + 1 - \alpha)^2 + \alpha^2 N\gamma] \tag{10}$$

By substituting (10) into (8) it follows that:

$$Q_n^*(\alpha) = a(1-\alpha)(\gamma + 1 - \alpha)/[(\gamma + 1 - \alpha)^2 + \alpha^2 N\gamma] \tag{11}$$

Let's define the *self-enforcing (SE) IEA*. We recall a concept developed for the analysis of cartel stability by D'Aspremont et al. (1983). We assume that we have $\alpha N$ signatories: (Table 1)

**Definition 2.1** An IEA is self-enforcing if and only if it satisfies the following conditions:

$$\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \tag{12}$$

and

$$\pi_n(\alpha) \geq \pi_s(\alpha + 1/N) \tag{13}$$

**Table 1** A simple algorithm for finding $\alpha$ for one self-enforcing IEA

| |
|---|
| $for \quad i = 1 \quad to \quad N$ |
| $\alpha = i/N$ |
| if $\quad [\pi_s(\alpha) \geq \pi_n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi_s(\alpha + 1/N)]$ |
| save $\alpha$ |

If the inequality (12) is satisfied, then no signatory wants to withdraw from the IEA. It will reduce costs, but it will reduce benefits even more. This aspect of stability is known as *Internal Stability*. Similarly no nonsignatory wants to join the IEA, see Eq. 13. It will raise benefits, but it will raise costs even more. This aspect of stability is known as *External Stability*. For both cases *any movement of any country (joining or withdrawing from IEA) will reduce its profit*.

A very simple algorithm for finding $\alpha(i =$ number of signatories) can be: Please note that for our function's specification, we have only one $\alpha$. We introduce a new formulation of our problem. We formulate it *as a nonlinear optimization*, because this formulation can be used to solve the problem of *two self-enforcing IEA* too.

$$\max \alpha \tag{14}$$

$$s.t \quad [\pi_s(\alpha) \geq \pi n(\alpha - 1/N) \wedge \pi_n(\alpha) \geq \pi s(\alpha + 1/N)] \tag{15}$$

The problem can be formulated as of minimization one.[1]

## 3 Our Model, One Self-Enforcing IEA with Asymmetric Countries

In order to have a more realistic picture of coalition formation, *asymmetric countries* are introduced.[2] There are two types of countries, *type one and type two*. Type one can be non-signatory or signatory of the first IEA, while type two can be only non-signatory.

Let's summarize the notation that we use in this section:

$N$ : total number of countries
$\alpha_1 N$ : total number of countries in the IEA (or coalition), which are countries of type one
$\alpha_2 N$ : total number of non-signatories, which are countries of type one,
$\alpha_3 N$ : total number of non-signatories, which are countries of type one,
$Q = Q_s + Q_n$, where $Q$ : total abatement level,
$Q_s$: total abatement level of coalition of signatories,
$Q_n$: total abatement level of non-signatories,
$Q_n = Q_{n_1} + Q_{n_2}$,

[1] $\alpha N$ usually will not be an integer number, but we round down, then find $\alpha_{new} = rounddown(\alpha N)/N$. Using Matlab Optimization Toolbox, minimization proved to be more robust. In our experience, the starting point can be slightly problematic, but as we know that $\alpha \in [0, 1]$ it is easily overcome.

[2] Diamantoudi and Sartzetakis (2001) show that an IEA's in Barrett's model with symmetric countries, can have mostly four countries, if emissions are positive. In order to avoid this shortcoming, asymmetric countries are introduced.

$Q_{n_1}$: total abatement levels of non-signatories of first type,
$Q_{n_2}$: total abatement levels of non-signatories of second type,
$\pi_s$ : the profit of a country of the coalition of signatories,
$\Pi_s = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_s$ the total profit of the coalition of signatories,
$q_s$: the abatement level of a country of the coalition of signatories,
$\pi_{n_1}$ : the profit of a country of non-signatories of first type,
$\Pi_{n_1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{n_1}$ the total profit of non-signatories of first type,
$q_{n_1}$: the abatement level of a country of of non-signatories of first type,
$\pi_{n_2}$: the profit of a country of of non-signatories of second type,
$\Pi_{n_2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{n_2}$ the total profit of non-signatories of second type,
$q_{n_2}$: the abatement level of a country of non-signatories of second type,

The profit function of a country $i$ for the first coalition, non-signatories of first type and for non-signatories of second type, is given by:

$$\begin{aligned}
\pi_s &= b(a_1 Q - Q^2/2)/N - c_1 q_{s_1}^2/2 \\
\pi_{n_1} &= b(a_1 Q - Q^2/2)/N - c_1 q_{n_1}^2/2 \\
\pi_{n_2} &= b(a_2 Q - Q^2/2)/N - c_2 q_{n_2}^2/2
\end{aligned}$$

The first type of countries have parameters $a_1, b$ and $c_1$, while the second type of countries have parameters $a_2$, $b$ and $c_2$.

As there are asymmetric countries, in order to find if the coalition is myopic stable, we need to solve more than one nonlinear optimization problem. This occurs because as alpha changes, the objective function and non-linear constrains change their form.

In the initial nonlinear optimization problem (16–18), the $\alpha_1 N$ players of the first type maximize their total welfare (which is the objective function) and are the Stackelberg leader, see Eq. 16. There are $\alpha_2 N$ members of non-signatories of first type. Every non-signatory maximizes its own welfare. This is the reaction function of non-signatories of first type and the first constrain of our initial optimization problem. The non-signatories are Stackelberg followers, see Eq. 17. There are $\alpha_3 N$ non-signatories of the second type. Each of them maximizes its own welfare, this is the reaction function of non-signatories of second type, and the second constrain of our initial optimization problem. They are also Stackelberg follower, see Eq. 18.

$$\max(\alpha_1 N \pi_s) \tag{16}$$

s.t

$$d(\pi_{n_1})/d(q_{n_1}) = 0 \Longleftrightarrow \alpha_1 N q_s + (\alpha_2 + \gamma_1) N q_{n_1} + \alpha_3 N q_{n_2} = a_1 \tag{17}$$
$$d(\pi_{n_2})/d(q_{n_2}) = 0 \Longleftrightarrow \alpha_1 N q_s + \alpha_2 N q_{n_1} + (\alpha_3 + \gamma_2) N q_{n_2} = a_2 \tag{18}$$

Solving the initial optimization problem (16–18), we receive the abatement level for a single country of the coalition, non-signatories of first type and second type $q_s^1$, $q_{n_1}^1$ and $q_{n_2}^1$. Then we are able to calculate the profit of a single player of the first coalition, non-signatories of first type and second type which are necessary to find if our coalition is myopic stable. We name these profits by $\pi_s^1$, $\pi_{n_1}^1$ and $\pi_{n_2}^1$.

Then we suppose that a non-signatory of first type joins the coalition (which has only the first type of players). This implies that $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_2 = \alpha_2 - 1./N$. For the new alpha's we solve again the optimization problem (16–18) and find the profit of a single player for the coalition, non-signatories of first type and second type (after we have found the abatement levels of them), which we name by $\pi_s^2$, $\pi_{n_1}^2$ and $\pi_{n_2}^2$.

After reassigning the alpha's again to their starting values, we suppose that a member of first coalition, which is a first type player becomes a non-signatory. This implies that $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_2 = \alpha_2 + 1./N$. For the new alpha's we solve again the optimization problem (16–18) and find the profit of a single player for the coalition, non-signatories of first type and second type (after we have found the abatement levels of them), which we name by $\pi_s^3$, $\pi_{n_1}^3$ and $\pi_{n_2}^3$.

After reassigning the alpha's again to their starting values, we suppose that a non-signatory of second type joins the coalition (which has only first type players). This implies that $\alpha_3 = \alpha_3 - 1./N$. For the new alpha's we solve the new optimization problem (19–21). *In this optimization problem, we have to treat the abatement level of the country that leaves the non-signatories of second type and joins the coalition as a new variable,* $q_s^{4*}$. After solving the optimization problem, we receive the abatement levels for a single country that belongs to the coalition, non-signatories of first type, second type and the single country that leaves the non-signatories of second type and joins the coalition; we name these abatement levels by $q_s^4$, $q_{n_1}^4$, $q_{n_2}^4$ and $q_s^{4*}$. Then we are able to find the profit of a single player that belongs to coalition, non-signatories of first type, second type and the single country that leaves the non-signatories of second type and joins the coalition; we name these profits by $\pi_s^4$, $\pi_{n_1}^4$, $\pi_{n_2}^4$ and $\pi_s^{4*}$.

$$\max(\alpha_1 N \pi_s + \pi_s^{4*}) \tag{19}$$

s.t

$$d(\pi_{n_1})/d(q_{n_1}) = 0 \Longleftrightarrow \alpha_1 N q_s + (\alpha_2 + \gamma_1) N q_{n_1} + \alpha_3 N q_{n_2} + q_s^{4*} = a_1 \tag{20}$$
$$d(\pi_{n_2})/d(q_{n_2}) = 0 \Longleftrightarrow \alpha_1 N q_s + \alpha_2 N q_{n_1} + (\alpha_3 + \gamma_2) N q_{n_2} + q_s^{4*} = a_2 \tag{21}$$

We state below the conditions which are satisfied, when a myopic stable coalition of first type of countries is build.

**Definition 3.1** A coalition of first type of countries is myopic stable if and only if the conditions (22–24) are satisfied:

$$\pi_{n_1}^1 \geq \pi_s^2 \Longleftrightarrow \text{if a nonsignatory of the first type joins the coalition it does not increase its profit} \tag{22}$$
$$\pi_s^1 \geq \pi_{n_1}^2 \Longleftrightarrow \text{if a member of the coalition joins the nonsignatories it doesnot increase its profit} \tag{23}$$
$$\pi_{n_2}^1 \geq \pi_s^{4*} \Longleftrightarrow \text{if a nonsignatory of the second type joins the coalition it doesnot increase its profit} \tag{24}$$

**Table 2** Algorithm for finding a myopic stable coalition

| |
|---|
| $a_1, a_2, b_1, b_2, c, \alpha_1, \alpha_2, \alpha_3, N$ are known parameters $\gamma_1 = c/b_1$ and $\gamma_2 = c/b_2$ optimization procedure finds the abatement levels $\mathbf{q}$, and then calculate profit $\pi$ for a country which belongs to the coalition or nonsignatories |
| Solving the initial optimization problem (16–18), we receive the abatement levels for a single country of the coalition ($C$), and nonsignatories of first type and second type $q_s^1, q_{n_1}^1$ and $q_{n_2}^1$ and calculate the profit for them $\pi_s^1, \pi_{n_1}^1$ and $\pi_{n_2}^1$ |
| $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_2 = \alpha_2 - 1./N$, we solve again the initial optimization problem (16–18) and calculate the profit of single player of $C$, and nonsignatories of first type and second type (after we have found the abatement levels of them), which we name by $\pi_s^2, \pi_{n_1}^2$ and $\pi_{n_2}^2$ |
| Reassign alpha's again to their initial values, $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_2 = \alpha_2 + 1./N$ |
| $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_2 = \alpha_2 + 1./N$, we solve again the initial optimization problem (16–18) and calculate the profit of single player of $C$, and nonsignatories of first type and second type (after we have found the abatement levels of them), which we name by $\pi_s^3, \pi_{n_1}^3$ and $\pi_{n_2}^3$ |
| Reassign alpha's again to their initial values, $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_2 = \alpha_2 - 1./N$ |
| Let $\alpha_3 = \alpha_3 - 1./N$, we solve the new optimization problem (19–21) and calculate the profit of single player of $C$, nonsignatories of first type and second type and the single country (after we have found the abatement levels of them) that leaves the nonsignatories of second type and joins $C$, which we name by $\pi_s^4, \pi_{n_1}^4, \pi_{n_2}^4$ and $\pi_s^{4*}$ |
| If $\pi_{n_1}^1 \geq \pi_s^2 \wedge \pi_s^1 \geq \pi_{n_1}^2 \wedge \pi_{n_2}^1 \geq \pi_s^{4*}$ then coalition $C$ is myopic stable |

After we solve all optimization problems, we inspect if conditions (22–24) are satisfied. Then, we know if a coalition is myopic stable or not. All the steps for finding a myopic stable coalition, which we explained, are also shortly described in Table 2.

We also find interesting to consider another way of forming an IEA (or coalition) with asymmetric countries, namely when all countries of second type build an IEA. The difference with the first approach is that, there are no signatories, which are the same type as the countries that form the coalition. The coalition behaves like a Stackelberg leader, and non-signatories behave like Stackelberg follower. Clearly there are $(\alpha_1 + \alpha_2)N$ non-signatories of first type, and $\alpha_3 N$ coalition members of second type; let $\alpha_1^* = \alpha_1 + \alpha_2$, so we have only $\alpha_1$ and $\alpha_3$.

As already mentioned, in order to find if a coalition is myopic stable, we need to solve more than one nonlinear optimization problem.

$$\max(\alpha_3 N \pi_s) \tag{25}$$

s.t

$$d(\pi_n)/d(q_n) = 0 \Longleftrightarrow (\alpha_1^* + \gamma_1)Nq_n + \alpha_3 N q_s = a_1 \tag{26}$$

Solving the new initial optimization problem (25–26), we receive the abatement level for a single country of the coalition and non-signatories $q_s^1$ and $q_n^1$. Then, we are able to calculate the profit of a single player of the first coalition and non-signatories, which are necessary to find if our coalition is myopic stable. We name these profits by $\pi_s^1$ and $\pi_n^1$.

We suppose that a member of coalition (which has only second type of players) leaves the coalition and becomes the only non-signatory of second type. This implies that $\alpha_3 = \alpha_3 - 1./N$. For the new alpha's, we solve the new optimization problem (27–29). *In this optimization problem, we have to treat (again) the abatement level of the country that leaves the coalition and joins the non-signatory as a new variable,* $q_n^{2*}$. After solving the optimization problem, we receive the abatement level for a country that belongs to the coalition, non-signatories and the single country that left the coalition and joined the non-signatories; we name these abatement levels by $q_s^2$, $q_n^2$ and $q_n^{2*}$. Then, we are able to find the single profit of countries that belong to coalition, non-signatories and the single country that left the coalition and joined the non-signatories; we name these profits by $\pi_s^2$, $\pi_n^2$ and $\pi_n^{2*}$.

$$\max(\alpha_3 N \pi_s) \tag{27}$$

s.t

$$d(\pi_n)/d(q_n) = 0 \Longleftrightarrow (\alpha_1^* + \gamma_1)Nq_n + \alpha_3 N q_s = a_1 \tag{28}$$

$$d(\pi_{n*})/d(q_{n*}) = 0 \Longleftrightarrow \alpha_1^* N q_n + (1 + \gamma_1 N)q_{n*} + \alpha_3 N q_s = a_2 \tag{29}$$

After reassigning the alpha's again to their starting values, we suppose that a non-signatory joins the coalition. This implies that $\alpha_1^* = \alpha_1^* - 1./N$. For the new alpha's, we solve the new optimization problem (30–31). *In this optimization problem, we have to treat (again) the abatement level of the non-signatory that joins the coalition as a new variable,* $q_s^{3*}$. The optimization problem provides us the abatement level for a country that belongs to the coalition, non-signatories and the single non-signatory that joined the coalition; we name these abatement levels by $q_s^3$, $q_n^3$ and $q_s^{3*}$. Then, we are able to find the single profit of country that belongs to coalition, non-signatories and the single non-signatory that joined the coalition; we name these profits by $\pi_s^3$, $\pi_n^3$ and $\pi_s^{3*}$.

$$\max(\alpha_3 N \pi_s) \tag{30}$$

s.t

$$d(\pi_n)/d(q_n) = 0 \Longleftrightarrow (\alpha_1^* + \gamma_1)Nq_n + \alpha_3 N q_s = a_1 \tag{31}$$

We state below the conditions which are satisfied, when a myopic stable coalition of second type of countries is built.

**Definition 3.2** A coalition of second type of countries is myopic stable if and only if the conditions (32–33) are satisfied:

$$\pi_n^1 \geq \pi_s^{2*} \Longleftrightarrow \text{if a nonsignatory joins the coalition it does not increase its profit.} \tag{32}$$

$$\pi_s^1 \geq \pi_n^{2*} \Longleftrightarrow \text{if a member of the coalition joins the nonsignatories it does not increase its profit.} \tag{33}$$

**Table 3** Algorithm for finding a myopic stable coalition

| |
|---|
| $a_1, a_2, b_1, b_2, c, \alpha_1, \alpha_2, \alpha_3, N$ are known parameters $\alpha_1^* = \alpha_1 + \alpha_2$, $\gamma_1 = c/b_1$ and $\gamma_2 = c/b_2$ optimization procedure finds the abatement levels $\mathbf{q}$, and then calculate profit $\pi$ for a country which belongs to the coalition or nonsignatories |
| Solving the initial optimization problem (25–26), we receive the abatement levels for a single country of the coalition ($C$), and nonsignatories $q_s^1$ and $q_n^1$ and calculate the profit for them $\pi_s^1$ and $\pi_n^1$ |
| $\alpha_3 = \alpha_3 - 1./N$, we solve the new initial optimization problem (27–29) and calculate the profit of single player of $C$, nonsignatories and the single country that left the coalition and joined the nonsigantories (after we have found the abatement levels of them), which we name by $\pi_s^2$, $\pi_n^2$ and $\pi_n^{2*}$ |
| Reassign alpha's again to their initial values $\alpha_3 = \alpha_3 + 1./N$ |
| $\alpha_1^* = \alpha_1^* - 1./N$, we solve the new initial optimization problem (30–31) and calculate the profit of single player of $C$, nonsignatories and the single country that left the nonsignatoies and joined the coalition (after we have found the abatement levels of them), which we name by $\pi_s^3$, $\pi_n^3$ and $\pi_s^{3*}$ If $\pi_s^1 \geq \pi_n^{2*} \wedge \pi_n^1 \geq \pi_s^{3*}$ then coalition $C$ is myopic stable |

Then after we solve all optimization problems, we test if conditions (32–33) are satisfied, and we know if a coalition is myopic stable or not. All the steps of for finding a myopic stable coalition, which we explained, are also shortly described in Table 3.

## 4 Our Model, Two Self-Enforcing IEA with Symmetric Countries

In the case of two self-enforcing agreements, we have two coalitions of signatories; the first coalition ($C_{s_1}$) with $\alpha_1 N$ countries, and the second one ($C_{s_2}$) with $\alpha_2 N$ countries, and $(1 - \alpha_1 - \alpha_2)N$ nonsignatories ($C_n$). Firstly, the coalition of signatories ($C_{s_1}$) (*Stackelberg leader*[3]) and the second coalition of signatories ($C_{s_2}$) (*which are Stackelberg follower*) are formed; they try to maximize their net-benefits; every coalition knows the number of countries in the other coalition. After observing the choice of signatories, every nonsignatory (*which are also Stackelberg followers*) maximizes its own net benefit by taking the abatement level of signatories coalition and other nonsignatories as given. Let $Q_{s_1}$ be the total abatement of $C_{s_1}$, $q_{s_1}$ be the single signatory abatement of $C_{s_1}$; let $Q_{s_2}$ be the total abatement of $C_{s_2}$, $q_{s_2}$ be the single signatory abatement of $C_{s_2}$; let $Q_n$ be the total abatement of $C_n$, $q_n$ be the single signatory abatement of $C_n$. The same arguments as before imply that $Q_{s_1} = \alpha_1 q_{s_1} N$, $Q_{s_2} = \alpha_2 q_{s_2} N$, $Q_n = (1 - \alpha_1 - \alpha_2) q_n N$.

Let's summarize the notation that we use in this section:

$\alpha = \alpha_1 + \alpha_2$,
$Q = Q_s + Q_n$,
$Q$ : total abatement level,
$Q_s$: total abatement level of two coalition of signatories,
$Q_n$: total abatement level of nonsignatories,
$Q_s = Q_{s_1} + Q_{s_2}$,

[3] Note that this sequential game can be easily changed by taking as Stackelberg leader $C_{s_2}$. Or by taking both of $C_{s_1}$ and $C_{s_2}$ as Stackelbergs leaders playing a simultaneous Nash-Cournot equilibrium between each-other.

$Q_{s_1}$: total abatement level of first coalition,
$Q_{s_2}$: total abatement level of second coalition,
$\pi_{s_1}$ : the profit of a country of first coalition of signatories,
$\Pi_{s_1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{s_1}$ the total profit of first coalition of signatories,
$q_{s_1}$: the abatement level of a country of first coalition of signatories,
$\pi_{s_2}$: the profit of a country of first coalition of signatories,
$\Pi_{s_2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{s_2}$ the total profit of second coalition of signatories,
$q_{s_2}$: the abatement level of a country of first coalition of signatories,
$\pi_n$: the profit of a country of nonsignatories,
$q_n$: the abatement level of a country of nonsignatories

The profit function of country $i$ for the first, the second coalition of signatories and for nonsignatories is given by:

$$\pi_{s_1} = b(aQ - Q^2/2)/N - cq_{s_1}^2/2$$
$$\pi_{s_2} = b(aQ - Q^2/2)/N - cq_{s_2}^2/2$$
$$\pi_n = b(aQ - Q^2/2)/N - cq_n^2/2$$

The Stackelberg game can be formulated as a nonlinear optimization problem (34–36), the $\alpha_1 N$ players maximize their total welfare (which is the objective function, see Eq. 34 and are the Stackelberg leader. The $\alpha_2 N$ members of second coalition maximize their total welfare, this is the reaction function of second coalition and the first constrain of our optimization problem, see Eq. 35. The second coalition is a Stackelberg follower. There are $\alpha_3 N$ players, which do not belong to any coalition. Each of them maximizes its own welfare, this is the reaction function of non-signatories and the second constrain of our optimization problem, see Eq. 36. They are also Stackelberg followers.

$$\max(\alpha_1 N \pi_{s_1}) \Longleftrightarrow d(\Pi_{s_1})/d(Q_{s_1}) = 0 \Longleftrightarrow Q_{s_1} = f(\alpha_1, \alpha_2, Q_{s_2}, Q_n) \quad (34)$$

s.t

$$d(\Pi_{s_2})/d(Q_{s_2}) = 0 \Longleftrightarrow Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1}, Q_n) \quad (35)$$
$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow Q_n = (1-\alpha)(a - Q_s)/(\gamma + 1 - \alpha)$$
$$= f(\alpha_1, \alpha_2, Q_{s_1}, Q_{s_2}) \quad (36)$$

The constrained optimization problem (34–36) can be transformed to a nonconstrained one. Firstly, we replace the Eq. 36 to Eq. 35 (and receive $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$). Afterward, we replace the Eqs. 36 and 35 to the objective function (34) (and receive[4] $Q_{s_1} = f(\alpha_1, \alpha_2)$). Clearly, after these replacements, we have a nonconstrain optimization problem. As we have $Q_{s_1} = f(\alpha_1, \alpha_2)$, we replace it (now backward) in $Q_{s_2} = f(Q_{s_1}, \alpha_1, \alpha_2)$ and have $Q_{s_2} = f_{s_2}(\alpha_1, \alpha_2)$. We replace both of them in Eq. 36

[4] We do not write explicitly $Q_{s_2} = f(\alpha_1, \alpha_2, Q_{s_1})$ and $Q_{s_1} = f(\alpha_1, \alpha_2)$ because of the lengthy analytical formula.

then we receive $Q_n = f_n(\alpha_1, \alpha_2)$. Finally we have all $\pi_{s_2}, \Pi_{s_2}, \pi_{s_1}, \Pi_{s_1}, \pi_n, \Pi_n$ as $f(\alpha_1, \alpha_2)$.

In order to find $\alpha_1$ and $\alpha_2$ we need to formulate a different optimization problem. We need the conditions of one self-enforcing agreements to be satisfied among three groups of countries, the coalition one of signatories, $(C_{s_1})$, the coalition two of signatories, $(C_{s_2})$ and the nonsignatories, $(C_n)$ in order to have *intercoalition stability*. This notion of intercoalition stability is firstly introduced (in a more general formulation) by Carraro (1999), which is an extension of myopic stability of D'Aspremont et al. (1983) when two (or more) coalitions are formed. The intercoalition stability means stable relations between $C_{s_2}$ and $C_n$, $C_{s_1}$ and $C_{s_2}$ as well as $C_{s_1}$ and $C_{s_2}$.

**Definition 4.1** We have intercoalition stability if and only if the following conditions (37–39) are satisfied:

$$\left[\pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)\right] \quad (37)$$
$$\left[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1, \alpha_2 + 1/N)\right] \quad (38)$$
$$\begin{aligned}&\left[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N)\right.\\ &\left.\wedge\ \pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)\right]\end{aligned} \quad (39)$$

It is important to note that conditions (37–39) together describe all possible changes among $C_{s_1}$, $C_{s_2}$ and $C_n$ if only one country is changing its position. Clearly any change in any country position reduces its profit. In other words, they guarantee stability among two coalitions and nonsignatories, so they guarantee intercoalition stability.

Now we are ready to formulate the nonlinear optimization problem that helps us to find $\alpha_1$ and $\alpha_2$.

$$\max(\alpha_1 + \alpha_2) \quad (40)$$
$$\left[\pi_{s_1}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1 - 1/N, \alpha_2) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2)\right] \quad (41)$$
$$\left[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_n(\alpha_1, \alpha_2 - 1/N) \wedge \pi_n(\alpha_1, \alpha_2) \geq \pi_{s_2}(\alpha_1, \alpha_2 + 1/N)\right] \quad (42)$$
$$\begin{aligned}&\left[\pi_{s_2}(\alpha_1, \alpha_2) \geq \pi_{s_1}(\alpha_1 + 1/N, \alpha_2 - 1/N) \wedge \pi_{s_1}(\alpha_1, \alpha_2)\right.\\ &\left.\geq\ \pi_{s_2}(\alpha_1 - 1/N, \alpha_2 + 1/N)\right]\end{aligned} \quad (43)$$

The constrains of above optimization problem are just the conditions (37), (38) and (39).

As one would expect the starting point and rounding are cumbersome.[5]

[5] The starting point is slightly problematic but with the help of the algorithm in Table 1 we can find a starting point for $\alpha_1$. As the interval of $\alpha_2$ is small, it is not difficult to find the second starting point. As with the case of one self-enforcing IEA, $\alpha_1 N$ and $\alpha_2 N$ will usually not be integer numbers, so we only can round both down and find the new $\alpha_1^{new} = rounddown(\alpha_1 N)/N$ and $\alpha_2^{new} = rounddown(\alpha_2 N)/N$. After rounding down, we check if six constrains are still satisfied (for one self-enforcing IEA, there were only two constrains).

## 5 Our Model, Two Self-Enforcing IEA with Asymmetric Countries

In this section, two IEA's are modeled by considering *asymmetric countries*. There are two types of countries, *type one and type two*. Type 1 can be a signatory or non-signatory of the first IEA, while all type 2 countries build the second IEA.[6]

Let's summarize the notation that we use in this section:

$N$ : total number of countries

$\alpha_1 N$ : total number of countries in the first IEA (or first coalition), which are countries of type one

$\alpha_2 N$ : total number of countries in the second IEA (or second coalition), which are countries of type two

$\alpha_3 N$ : total number of non-signatories, which are countries of type one,

$Q = Q_s + Q_n$, where $Q$ : total abatement level,

$Q_s$: total abatement level of two coalition of signatories,

$Q_n$: total abatement level of non-signatories,

$Q_s = Q_{s_1} + Q_{s_2}$,

$Q_{s_1}$: total abatement level of first coalition,

$Q_{s_2}$: total abatement level of second coalition,

$\pi_{s_1}$ : the profit of a country of first coalition of signatories,

$\Pi_{s_1} = \sum_1^{\alpha_1 N} \pi_i = \alpha_1 N \pi_{s_1}$ the total profit of first coalition of signatories,

$q_{s_1}$: the abatement level of a country of first coalition of signatories,

$\pi_{s_2}$: the profit of a country of first coalition of signatories,

$\Pi_{s_2} = \sum_1^{\alpha_2 N} \pi_i = \alpha_2 N \pi_{s_2}$ the total profit of second coalition of signatories,

$q_{s_2}$: the abatement level of a country of first coalition of signatories,

$\pi_n$: the profit of a country of non-signatories,

$q_n$: the abatement level of a country of non-signatories.

The profit function of country $i$ for the first coalition, the second coalition of signatories and for non-signatories is given by:

$$\begin{aligned}
\pi_{s_1} &= b(a_1 Q - Q^2/2)/N - c_1 q_{s_1}^2/2 \\
\pi_{s_2} &= b(a_2 Q - Q^2/2)/N - c_2 q_{s_2}^2/2 \\
\pi_n &= b(a_1 Q - Q^2/2)/N - c_1 q_n^2/2
\end{aligned}$$

It is clear that first type of countries have parameters $a_1$, $b$ and $c_1$, while second type of countries have parameters $a_2$, $b$ and $c_2$.

As there are asymmetric countries in order to find if a couple of coalitions are myopic stable, we need to solve more than one nonlinear optimization problem. It occurs because, as alpha changes the objective function and non-linear constrains change their forms. This is a central point and we are going to explain in the following paragraphs.

In the initial nonlinear optimization problem (44–46), the $\alpha_1 N$ players of the first type maximize their total welfare (which is the objective function, see Eq. 44) and are

[6] Our numerical computations show that all countries of second type must build one IEA. If not, then two myopic stable coalitions are impossible to be formed. We will come back to this peculiar point in sections of Simulations and Conclusions.

the Stackelberg leader. The $\alpha_2 N$ members of second coalition maximize their total welfare, this is the reaction function of second coalition and the first constrain of our optimization problem, see Eq. 45. The second coalition is a Stackelberg follower. There are $\alpha_3 N$ players, which do not belong to any coalition. Each of them maximizes its own welfare, this is the reaction function of non-signatories and the second constrain of our optimization problem, see Eq. 46. They are also Stackelberg followers.

$$\max(\alpha_1 N \pi_{s_1}) \tag{44}$$

s.t

$$d(\Pi_{s_2})/d(Q_{s_2}) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + (\gamma_2/\alpha_2 + \alpha_2 N) q_{s_2} + \alpha_3 N q_n = a_2 \tag{45}$$

$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + (\alpha_3 + \gamma_1) N q_n = a_1 \tag{46}$$

Solving the initial optimization problem (44–46), we receive the abatement level for a single country of the first coalition, second coalition and non-signatories $q^1_{s_1}$, $q^1_{s_2}$ and $q^1_n$. It follows that we are able to calculate the profit of a single player of the first coalition, second coalition and non-signatories, which are necessary to find if our coalitions are myopic stable. We name these profits by $\pi^1_{s_1}$, $\pi^1_{s_2}$ and $\pi^1_n$.

Then, we suppose that a non-signatory (which is a player of first type) joins the first coalition (which has only players of first type). This implies that $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_3 = \alpha_3 - 1./N$. For the new alpha's, we solve again the optimization problem (44–46) and find the profit of a single player of the first coalition, second coalition and non-signatories (after we have found the abatement levels of them), which we name by $\pi^2_{s_1}$, $\pi^2_{s_2}$ and $\pi^2_n$.

After reassigning the alpha's again to their starting values, we suppose that a member of first coalition joins the non-signatories. This implies that $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_3 = \alpha_3 + 1./N$. For the new alpha's, we solve again the optimization problem (44–46) and find the profit of a single player of the first coalition, second coalition and non-signatories, which we name by $\pi^3_{s_1}$, $\pi^3_{s_2}$ and $\pi^3_n$.

After reassigning the alpha's again their starting values, we suppose that a member of first coalition joins the second coalition (which has only players of second type). This implies that $\alpha_1 = \alpha_1 - 1./N$. For the new alpha's, we solve the new optimization problem (47–49). *In this optimization problem, we have to treat the abatement level of the country that leaves the first coalition and joins the second one as a new variable,* $q^{4*}_{s_2}$. After solving the optimization problem, we receive the abatement level for a single country of the first coalition, second coalition, non-signatories and the single country that leaves the first coalition and joins the second one; we name these abatement levels by $q^4_{s_1}$, $q^4_{s_2}$, $q^4_n$ and $q^{4*}_{s_2}$. Afterwards, we are able to find the profit of a single player of the first coalition, second coalition, non-signatories, and of the single country that leaves the first coalition and joins the second one; we name these profits by $\pi^4_{s_1}$, $\pi^4_{s_2}$, $\pi^4_n$ and $\pi^{4*}_{s_2}$.

$$\max(\alpha_1 N \pi_{s_1}) \tag{47}$$

s.t

$$d(\Pi_{s_2})/d(Q_{s_2}) = 0 \Longleftrightarrow 2\alpha_1 N q_{s_1} + (2\alpha_2 N + 1/\alpha_2) q_{s_2} + 2\alpha_3 N q_n + (\gamma_1 N + 2) q_{s_2}^* = a_1 + a_2 \tag{48}$$

$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + (\alpha_3 + \gamma_1) N q_n + q_{s_2}^* = a_1 \tag{49}$$

After reassigning the alpha's again to their starting values, we suppose that a member of the second coalition joins the first coalition. This implies that $\alpha_2 = \alpha_2 - 1./N$. For the new alpha's, we solve the new optimization problem (50–52). *In this optimization problem, we have to treat (again) the abatement level of the country that leaves the second coalition and joins the first one as a new variable,* $q_{s_1}^{5*}$. After solving the optimization problem, we receive the abatement level for a country of the first coalition, second coalition, non-signatories and the single country that leaves the second coalition and joins the first one; we name these abatement levels by $q_{s_1}^5$, $q_{s_2}^5$, $q_n^5$ and $q_{s_1}^{5*}$. Afterwards, we are able to find the profit of a player of the first coalition, second coalition, non-signatories the country that leaves the first coalition and joins the second one; we name these profits by $\pi_{s_1}^5$, $\pi_{s_2}^5$, $\pi_n^5$ and $\pi_{s_1}^{5*}$.

$$\max(\alpha_1 N \pi_{s_1} + \pi_{s_1}^{5*}) \tag{50}$$

s.t

$$d(\Pi_{s_2})\,/\,d(Q_{s_2}) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + (\alpha_2 N + \gamma_2\,/\,\alpha_2) N q_{s_2} + \alpha_3 N q_n + q_{s_1}^* = a_2 \tag{51}$$

$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + (\alpha_3 + \gamma_1) N q_n + q_{s_1}^* = a_1 \tag{52}$$

Now we are able to state the conditions when the first coalition is myopic stable.

**Definition 5.1** The first coalition is myopic stable if and only if the conditions 53–56 are satisfied:

$$\pi_n^1 \geq \pi_{s_1}^2 \Longleftrightarrow \text{if a nonsignatory joins the first coalition, it does not increase its profit} \tag{53}$$

$$\pi_{s_1}^1 \geq \pi_n^3 \Longleftrightarrow \text{if a member of the first coalition joins the nonsignatories, it does not increase its profit} \tag{54}$$

$$\pi_{s_1}^1 \geq \pi_{s_2}^{4*} \Longleftrightarrow \text{if a member of the first coalition joins the second coalition, it does not increase its profit} \tag{55}$$

$$\pi_{s_2}^1 \geq \pi_{s_1}^{5*} \Longleftrightarrow \text{if a member of the second coalition joins the first coalition, it does not increase its profit} \tag{56}$$

Clearly the conditions 55 and 56 has to be satisfied when the first coalition is myopic stable, but they are not the only ones as we like the second coalitions to be myopic stable too. In order to find other conditions that are satisfied when the second coalition is myopic stable we need to solve some other optimizations problems.

After reassigning the alpha's again to their starting values, we suppose that a member of the second coalition joins the non-signatories. This implies that $\alpha_2 = \alpha_2 - 1./N$. For the new alpha's, we solve the new optimization problem (57–60). *In this optimization problem, we have to treat (again) the abatement level of the country that leaves the second coalition and joins the non-signatories as a new variable,* $q_n^{6*}$. After solving the optimization problem, we receive the abatement level for a country of the first coalition, second coalition, non-signatories and the country that leaves the second coalition and joins the non-signatories; we name these abatement levels by $q_{s_1}^6$, $q_{s_2}^6$, $q_n^6$ and $q_n^{6*}$. Then, we are able to find the profit of a player of the first coalition, second coalition, non-signatories and the country that leaves the second coalition and joins the non-signatories; we name these profits by $\pi_{s_1}^6$, $\pi_{s_2}^6$, $\pi_n^6$ and $\pi_n^{6*}$.

$$\max(\alpha_1 N \pi_{s_1}) \tag{57}$$

s.t

$$d(\Pi_{s_2})/d(Q_{s_2}) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + (\alpha_2 N + \gamma_2/\alpha_2) N q_{s_2} + \alpha_3 N q_n + q_n^* = a_2 \tag{58}$$

$$d(\Pi_n)/d(q_n^*) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + (\alpha_3 + \gamma_1) N q_n + q_n^* = a_1 \tag{59}$$

$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + \alpha_3 N q_n + (1 + \gamma_2 N) q_n^* = a_2 \tag{60}$$

After reassigning the alpha's again to their starting values, we suppose that a member of the non-signatories joins the second coalition. This implies that $\alpha_3 = \alpha_3 - 1./N$. For the new alpha's, we solve the new optimization problem (61–63). *In this optimization problem, we have to treat (again) the abatement level of the country that leaves the non-signatories and joins the second coalition as a new variable,* $q_{s_2}^{7*}$. After solving the optimization problem, we receive the abatement level for a country of the first coalition, second coalition, non-signatories and the country that leaves the non-signatories and joins the second coalition; we name these abatement levels by $q_{s_1}^7$, $q_{s_2}^7$, $q_n^7$ and $q_{s_2}^{7*}$. Then, we are able to find the profit of a player of the first coalition, second coalition, non-signatories and the country that leaves the non-signatories and joins the second coalition; we name these profits by $\pi_{s_1}^7$, $\pi_{s_2}^7$, $\pi_n^7$ and $\pi_{s_2}^{7*}$.

$$\max(\alpha_1 N \pi_{s_1}) \tag{61}$$

s.t

$$d(\Pi_{s_2})/d(Q_{s_2}) = 0 \Longleftrightarrow 2\alpha_1 N q_{s_1} + (2\alpha_2 N + 1/\alpha_2) q_{s_2} + 2\alpha_3 N q_n + (\gamma_1 N + 2) q_{s_2}^* = a_1 + a_2 \tag{62}$$

$$d(\Pi_n)/d(q_n) = 0 \Longleftrightarrow \alpha_1 N q_{s_1} + \alpha_2 N q_{s_2} + (\alpha_3 + \gamma_1) N q_n + q_{s_2}^* = a_1 \tag{63}$$

**Definition 5.2** The second coalition is myopic stable if and only if the conditions 53–56 are satisfied:

$$\pi_{s_1}^1 \geq \pi_{s_2}^{4*} \iff \text{if a member of the first coalition joins the second coalition, it does not increase its profit} \tag{64}$$

$$\pi_{s_2}^1 \geq \pi_{s_1}^{5*} \iff \text{if a member of the second coalition joins the first coalition, it does not increase its profit} \tag{65}$$

$$\pi_{s_2}^1 \geq \pi_{n}^{6*} \iff \text{if a member of the second coalition joins the nonsignatories, it does not increase its profit} \tag{66}$$

$$\pi_{n}^1 \geq \pi_{s_2}^{7*} \iff \text{if a nonsignatory joins the second coalition, it does not increase its profit} \tag{67}$$

Note that the conditions (55–56) are equivalent to conditions (64–65). As a consequence, both coalitions are myopic stable when six conditions are satisfied, namely (53–56) and (66–67). This concept of intercoalition stability is initially presented (in a more general formulation) by Carraro (1999), which is a development of myopic stability concept of D'Aspremont et al. (1983) when two (or more) IEA's are built.

After we solve all optimization problems, we test if six conditions are satisfied, and we know if both coalitions are myopic stable or not. All the steps for finding myopic stable coalitions, which we explained, are also shortly described in Table 4.

## 6 Simulation Results

Firstly, we introduce the simulation[7] results for two myopic stable coalitions with symmetric countries.

As we know from simulations that the important parameters are $c$ (also $\gamma$) and $N$, we introduce results by varying these parameters,[8] see Tables 5 and 6.

We derive the main conclusion that if the damage cost is relative big ($c$ large, which implies also $\gamma$ large), and if the number of countries is small then two coalitions improve the welfare and abatement level significantly compared to one coalition. In all cases, a higher N implies less additional welfare and abatement due to the second coalition. So, a second coalition is more effective with a small number of countries than with a large number.

[7] All our simulations are performed by using the MATLAB Optimization Toolbox. The computer programs can be provided to the reader on request.

[8] We respect the conditions developed by Diamantoudi and Sartzetakis (2001) for the Barrett model, which guarantee positive emissions in case of symmetric countries. These conditions mainly request that the cost from pollution abatement (it means $c$ and $\gamma$) has to be sufficient high, which implies that emissions decreasing worth. In case of asymmetric countries, it is more difficult (and probably impossible) to develop conditions similar to Diamantoudi and Sartzetakis (2001), but we respect the principle that the cost from pollution abatement are high, which implies that emissions decreasing is "interesting".

**Table 4** Algorithm for finding myopic stable coalitions

| |
|---|
| $a_1, a_2, b_1, b_2, c, \alpha_1, \alpha_2, \alpha_3, N$ are known parameters $\gamma_1 = c/b_1$ and $\gamma_2 = c/b_2$ optimization problems find the abatement levels $\mathbf{q}$, and then calculate profit $\pi$ for a country which belongs to coalitions or nonsignatories |
| Solving the initial optimization problem (44–46), we receive the abatement levels for a single country of the first coalition ($C_1$), second coalition ($C_2$) and nonsignatories $q_{s_1}^1, q_{s_2}^1$ and $q_n^1$ and calculate the profit for them $\pi_{s_1}^1, \pi_{s_2}^1$ and $\pi_n^1$ |
| Let $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_3 = \alpha_3 - 1./N$, we solve again the initial optimization problem (44–46) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), which we name by $\pi_{s_1}^2, \pi_{s_2}^2$ and $\pi_n^2$ |
| Reassign alpha's again to their initial values, $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_3 = \alpha_3 + 1./N$ |
| Let $\alpha_1 = \alpha_1 - 1./N$ and $\alpha_3 = \alpha_3 + 1./N$, we solve again the initial optimization problem (44–46) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), which we name by $\pi_{s_1}^3, \pi_{s_3}^2$ and $\pi_n^3$ |
| Reassign alpha's again to their initial values, $\alpha_1 = \alpha_1 + 1./N$ and $\alpha_3 = \alpha_3 - 1./N$ |
| Let $\alpha_1 = \alpha_1 - 1./N$, we solve the new optimization problem (47–49) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), and the single country that leaves $C_1$ and joins $C_2$, which we name by $\pi_{s_1}^4, \pi_{s_2}^4, \pi_n^4$ and $\pi_{s_2}^{4*}$ |
| Reassign alpha's again to their initial values, $\alpha_1 = \alpha_1 + 1./N$ |
| Let $\alpha_2 = \alpha_2 - 1./N$, we solve the new optimization problem (50–52) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), and the single country that leaves $C_2$ and joins $C_1$, which we name by $\pi_{s_1}^5, \pi_{s_2}^5, \pi_n^5$ and $\pi_{s_2}^{5*}$ |
| Reassign alpha's again to their initial values, $\alpha_2 = \alpha_2 + 1./N$ |
| Let $\alpha_2 = \alpha_2 - 1./N$, we solve the new optimization problem (57–59) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), and the single country that leaves $C_2$ and joins the nonsignatories, which we name by $\pi_{s_1}^6, \pi_{s_2}^6, \pi_n^6$ and $\pi_{s_2}^{6*}$ |
| Reassign alpha's again to their initial values, $\alpha_2 = \alpha_2 + 1./N$ |
| Let $\alpha_3 = \alpha_3 - 1./N$, we solve the new optimization problem (61–63) and calculate the profit of single player of $C_1$, $C_2$ and nonsignatories (after we have found the abatement levels of them), and the single country that leaves the nonsignatories and joins $C_2$, which we name by $\pi_{s_1}^7, \pi_{s_2}^7, \pi_n^7$ and $\pi_{s_2}^{7*}$ If $\pi_n^1 \geq \pi_{s_1}^2 \wedge \pi_{s_1}^1 \geq \pi_n^3 \wedge \pi_{s_1}^1 \geq \pi_{s_2}^{4*} \wedge \pi_{s_2}^1 \geq \pi_{s_1}^{5*} \wedge \pi_{s_2}^1 \geq \pi_n^{6*} \wedge \pi_n^1 \geq \pi_{s_2}^{7*}$ then $C_1$ and $C_2$ are myopic stable |

The most interesting case remains the model of two myopic stable coalitions with asymmetric countries.

Our simulations show that if *two myopic stable coalitions are formed*, the first type of countries have the parameter $a_1$ two or three times bigger than the parameter $a_2$ of second type of countries. The first type of countries have also the parameter $c_1$ two or three times smaller than the parameter $c_2$ of second type of countries.

Our numerical computations show that all countries of second type must build one IEA. If not, then two myopic coalitions are impossible to be formed. It follows an important conclusion, namely all countries that have fewer benefits and higher cost from pollution abatement must build a coalition. Then, there is hope that two myopic stable coalition can be formed.

Tables 7, 9 and 11 present cases where two IEA's worsen the welfare and abatement levels compared to one IEA. On the opposite Table 8, 10 and 12 introduce a case where two IEA's improve the welfare and abatement levels compared to one IEA.

**Table 5** Comparing the abatement levels and benefits between one and two self-enforcing IEA *for different* **c**

| | A second s.e IEA increases welfare and abatement | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $a$ | $b$ | $c$ | $N$ | | | | | | |
| | 100 | 0.25 | 1.5 | 10 | | | | | | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| One coalition | 0.2* | – | 2.5* | – | 1.4* | 32.5* | – | 35.6* | 16.1* | 349.6* |
| Two coalitions | 0.3* | 0.2* | 3.4* | 2.4* | 1.3* | 39.4* | 43.9* | 46.9* | 21.6* | 440.7* |
| | $a$ | $b$ | $c$ | $N$ | | | | | | |
| | 100 | 0.25 | 1 | 10 | | | | | | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Full noncooperative | 0 | – | – | – | 2 | – | – | 43 | 20 | 430 |
| Full cooperative | 1 | – | 7.14 | – | – | 89.29 | – | – | 71.4 | 892.9 |
| One coalition | 0.2* | – | 3.2* | – | 1.9* | 43.8* | – | 47.2* | 22.1* | 465.3* |
| Two coalitions | 0.3* | 0.2* | 4.4* | 3.2* | 1.8* | 51.4* | 56.1* | 59.6* | 28.5* | 564.2* |

The symbol * we use to mark stability abatement values, and it is valid for all tables

**Table 6** Comparing the abatement levels and benefits between one and two self-enforcing IEA with symmetric countries *for different* ***N***

| | A second IEA increases welfare and abatement | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $a$ | $b$ | $c$ | $N$ | | | | | | |
| | 100 | 25 | 150 | 10 | | | | | | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Full noncooperative | 0 | – | – | – | 1.43 | – | – | 3163.3 | 14.3 | 31632.7 |
| Full cooperative | 1 | – | 6.25 | – | – | 7812.5 | – | – | 62.5 | 78125 |
| One coalition | 0.2* | – | 2.5* | – | 1.4* | 3248.4* | – | 3558.3* | 16.1* | 34962.8* |
| Two coalitions | 0.3* | 0.2* | 3.4* | 2.4* | 1.3* | 3942.6* | 4385.2 | 4693.4* | 21.6* | 44065.4* |
| | $a$ | $b$ | $c$ | $N$ | | | | | | |
| | 100 | 25 | 150 | 20 | | | | | | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Full noncooperative | 0 | – | – | – | 0.71 | – | – | 1619.9 | 14.3 | 32398 |
| Full cooperative | 1 | – | 3.85 | – | – | 4807.7 | – | – | 76.9 | 96153.9 |
| One coalition | 0.1* | – | 1.2* | – | 0.7* | 1716.1* | – | 1518.1* | 15.2* | 34171.3* |
| Two coalitions | 0.15* | 0.1* | 1.8* | 1.2* | 0.7* | 1811.6* | 1937.3* | 2013.0* | 18.0* | 39504.3* |
| | $a$ | $b$ | $c$ | $N$ | | | | | | |
| | 100 | 25 | 150 | 100 | | | | | | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Full noncooperative | 0 | – | – | – | 0.14 | – | – | 330.1 | 14.3 | 33010.2 |
| Full cooperative | 1 | – | 0.94 | – | – | 1179.2 | – | – | 94.3 | 117924.5 |
| One coalition | 0.03* | – | 0.37* | – | 0.14* | 333.9* | – | 342.5* | 14.86 | 34219.7* |
| Two coalitions | 0.03* | 0.02* | 0.36* | 0.24* | 0.14* | 337.7* | 343.2* | 346.1* | 15.03* | 34583.0* |

**Table 7** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of first type

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
| | 104 | 30 | 1.5 | 2.5 | 4.8 | 10 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 7.2 | 3.8 | 565.5 | −13.2 | 54.9 | 2761.5 | | | | |
| Full noncooperative | 4.8 | 0.17 | 310.6 | 65.3 | 24.6 | 1879.2 | | | | |
| Coalition structure | $\alpha_1$ | $q_{s_1}$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s_1}$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.3* | 9.6* | 4.1* | −0.19* | 338.5* | 375.3* | 67.5* | 36* | 2258.8* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s_1}$ | $q_{s_2}$ | $q_n$ | $\pi_{s_1}$ | $\pi_{s_2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.3* | 0.5* | 7* | 4.4* | 0.007* | 349.4* | 443.5* | 64.7* | 29.9* | 2258.8* |

The second IEA worsens welfare and abatement

If the economical-environmental cost-benefit functions determine that the first myopic coalition is formed by first type of countries, then two IEA's worsen abatement and welfare compared to one IEA. The explanation is that the first countries have bigger benefits from pollution abatement (because of big $a_1$) and they have high abatement levels. As the second type of countries has smaller benefits from abatement, when they formed their second coalition (they increase also their abatement levels), but they impose to the first coalition a significant reduction of their abatement levels. Consequently, it follows that the welfare and abatement levels are worse compare to one coalition. On the other side, the non-signatories (of first or second type countries) have very low or negative abatement levels, which means that they have no possibility to increase their welfare by abating pollution. The myopic world has exhausted its resources to improve welfare and abatement levels.

But, if the economical-environmental cost-benefit functions affect that the first myopic coalition is formed by second type of countries, then two IEA's improve abatement and welfare compared to one IEA. As the first type of countries has bigger benefits from abatement, when they formed their second coalition, they perform a significant reduction of their abatement levels. Consequently, it follows that the welfare and abatement levels are improved compared to one coalition. The first coalition improved the welfare and abatement almost equally when the second coalition is formed or not. On the other side, the non-signatories (there only signatories of countries of first type) have low or negative abatement levels, but they cannot offset the improvement in welfare and abatement by second coalition. The myopic world can perform small improvement to welfare and abatement levels.

Even in models with asymmetric countries a higher N implies less additional welfare and abatement due to the second coalition. So, a second coalition is again more effective with a small number of countries than with a large number.

**Table 8** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of second type

| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 124 | 30 | 1.5 | 3.7 | 8 | 10 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 7.9 | 3.6 | 707.6 | −42.6 | 57.6 | 3325.1 | | | | |
| Full noncooperative | 4.1 | 0.16 | 334.2 | 62 | 21.6 | 1981.3 | | | | |
| Coalition structure | $\alpha_1^2$ | $q_{s1}^2$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s1}^2$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.5* | 4.1* | 0.54* | – | 359.1* | 62.8* | – | 23.1* | 2109.5* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.3* | 0.5* | 7.4* | 3.8* | 0.013* | 387.6* | 67.5* | 461.6* | 29.9* | 2423.4* |

The second IEA improves welfare and abatement

**Table 9** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of first type

| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 84 | 30 | 1.5 | 2.1 | 2.4 | 20 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 3.4 | 3 | 240 | −24.7 | 65.7 | 3476.5 | | | | |
| Full noncooperative | 1.9 | 0.02 | 148.7 | 33.7 | 29.4 | 2398.7 | | | | |
| Coalition structure | $\alpha_1$ | $q_{s_1}$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s_1}$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.15* | 3.5* | 1.8* | −0.071* | 151.5* | 33.5* | 160.7* | 32.3* | 2551.2* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s_1}$ | $q_{s_2}$ | $q_n$ | $\pi_{s_1}$ | $\pi_{s_2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.15* | 0.25* | 2.6* | 1.9* | −0.066* | 149.9* | 33.7* | 153.1* | 30.4* | 2455.7* |

The second IEA worsens welfare and abatement

**Table 10** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of second type

| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 124 | 30 | 1.5 | 4.1 | 8 | 20 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 4.9 | 2.5 | 474.9 | −113.7 | 87 | 6555 | | | | |
| Full noncooperative | 1.8 | 0.03 | 215.9 | 33.4 | 26.8 | 3405.9 | | | | |
| Coalition structure | $\alpha_1^2$ | $q_{s1}^2$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s1}^2$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.25* | 1.77* | 0.11* | – | 218.2* | 33.4* | – | 27.1* | 3439.3* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.15* | 0.25* | 3.5* | 1.7* | −0.04* | 225.6* | 33.7* | 245* | 30.8* | 3785.7* |

The second IEA improves welfare and abatement

**Table 11** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of first type

| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 132 | 50 | 1.5 | 2.1 | 3.2 | 100 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 1.2 | 0.8 | 127.6 | −16.9 | 118 | 10589.7 | | | | |
| Full noncooperative | 0.6 | $610^{-4}$ | 79.7 | 18.7 | 49.9 | 7058.4 | | | | |
| Coalition structure | $\alpha_1$ | $q_{s1}$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s1}$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.03* | 1.05* | 0.6* | −0.003 | 79.79* | 79.9* | 18.7 | 50* | 7144.36* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.03* | 0.15* | 0.66* | 0.58* | −0.0007* | 79.96* | 80.77* | 18.75* | 50.71* | 7072.56* |

The second IEA worsens welfare and abatement

**Table 12** Comparing the abatement levels and benefits between one and two self-enforcing IEA *with asymmetric countries* where the first myopic stable coalition is built by countries of second type

| | $a_1$ | $a_2$ | $b$ | $c_1$ | $c_2$ | $N$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 126 | 30 | 1.5 | 4.1 | 3.6 | 100 | | | | |
| Coalition structure | $q_1$ | $q_2$ | $\pi_1$ | $\pi_2$ | $Q$ | $\Pi$ | | | | |
| Full cooperative | 1.21 | 1.01 | 114.5 | −42.3 | 108.7 | 9097.3 | | | | |
| Full noncooperative | 0.35 | 0.0004 | 49.5 | 6.7 | 29.9 | 4312.4 | | | | |
| Coalition structure | $\alpha_1^2$ | $q_{s1}^2$ | $q_{n_1}$ | $q_{n_2}$ | $\pi_{s1}^2$ | $\pi_{n_1}$ | $\pi_{n_2}$ | $Q$ | $\Pi$ | |
| One coalition | 0.15* | 0.35* | 0.003* | – | 49.6* | 6.7* | – | 29.93* | 4316.6* | |
| Coalition structure | $\alpha_1$ | $\alpha_2$ | $q_{s1}$ | $q_{s2}$ | $q_n$ | $\pi_{s1}$ | $\pi_{s2}$ | $\pi_n$ | $Q$ | $\Pi$ |
| Two coalitions | 0.15* | 0.03* | 0.47* | 0.35* | −0.006* | 49.6* | 49.8* | 6.7* | 30.09* | 4336.5* |

The second IEA improves welfare and abatement

## 7 Conclusions

The paper investigates the size and the improving capability of two self-enforcing IEA. An IEA is self-enforcing when no country wants to withdraw and no country wants to join the IEA. As we employ a simplified model the results must be interpreted with caution. Although, our work is less general than that of Yi and Shin, Bloch etc. we actually count up for asymmetric players and are able to compute the coalition sizes and optimal abatement levels.

We find that adding a second coalition improves welfare and environmental quality when the number of players is small and cost of pollution is high. That is, multiple coalitions help with continental environmental problems, but not with global environmental problems. At first sight, this conclusion is counterintuitive. Surely, bigger problems require a larger number of coalitions? However, the intuition behind the result follows from Barrett (1994) analysis. Barrett shows that stable coalitions are either small or irrelevant. “He also shows” / “Here we extend that result to show” that the share of players that cooperate grows if the number of players falls.

Consider a serious environmental problem with a large number of players. According to Barrett, only a small coalition would form. If we take the cooperative players out of the population, we are left with a still large number of players with a still serious environmental problem. In this subpopulation, only a small coalition would form. So, a second coalition does not add much. In fact, the additional constraint of inter-coalition stability more than offsets the gains of cooperation in the second coalition.

Now consider a serious environmental problem with a medium number of players. According to Barrett, only a small coalition would form. If we take these players out of the population, we are left with a smaller number of players with a considerable environmental problem. In this subpopulation, a larger coalition would form. That is, a second coalition does improve the welfare and environmental quality. In this case, the inter-coalition stability constraint reduces but not eliminates these gains.

If this intuition is correct, one may suspect that an environmental problem with a large number of players requires a high number of coalitions—and that only the "last" coalition will contribute to gains in welfare and environmental quality. However, with every additional coalition, the number of inter-coalition stability constraints grows combinatorially. This would offset these gains, and limits the number of coalitions that can form. This problem is deferred to future research.

Our numerical computations show that all countries of second type must build one IEA. If not, then two myopic coalitions are not possible to be formed. It follows an important conclusion, namely all countries that have fewer benefits and higher cost from pollution abatement must build a coalition. Then, there is hope that two myopic stable coalition can be formed.

Moreover, if the cost-benefit functions of pollution abatement determine that the first myopic coalition is formed by first type of countries, then two IEA's decrease abatement and welfare compared to one IEA. The clarification is that the first countries have bigger benefits from pollution abatement (because of big $a_1$) and they have high abatement levels. As the second type of countries has smaller benefits from abatement, when they formed their second coalition (they increase also their abatement levels) but they indirectly impose to the first coalition a significant reduction of their abatement levels. Consequently, it follows that the welfare and abatement levels are decreased compare to one coalition. On the other side, the non-signatories (of first or second type countries) have very low or negative abatement levels, which means that they are not able to improve their welfare by abating pollution.

But, if the cost-benefit functions of the pollution abatement effect that the first myopic coalition is formed by second type of countries, then two IEA's improve abatement and welfare compared to one IEA. As the first type of countries has bigger benefits from abatement, when they formed their second coalition, they perform a significant reduction of their abatement levels. Consequently, it follows that the welfare and abatement levels are improved compared to one coalition. The first coalition improves the welfare and abatement almost equally when the second coalition is formed or not. On the other side, the non-signatories (there only signatories of countries of first type) have low or negative abatement levels, but they cannot offset the improvement in welfare and abatement by second coalition.

As always, further research is needed in independence cost function, issue linkage, repeated games, uncertainty or limited information.

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